NASA TECHNICAL TRANSLATION

NASA TT F-11,738

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EXPERIMENTAL DETERMINATION OF GRAPHITE ABLATION RATES UNDER CONDITIONS OF SUBSTANTIAL NONISOTHERMALITY

A. I. Leont'yev, E. P. Volchkov, Ye.G. Zaulichnyy, Ye. I. Sinayko

Translation of "Eksperimental'noye Opredeleniye Skorosti Unosa Grafita v Usloviyakh Sushchestvennoy Neyizotermichnosti"
Fizika Goreniya i Vzryva, Vol. 3, No. 2, pp. 248-254, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JUNE 1968

NASA TT F-11,738

EXPERIMENTAL DETERMINATION OF GRAPHITE ABLATION RATES UNDER CONDITIONS OF SUBSTANTIAL NONISOTHERMALITY

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ABSTRACT. Investigation of the ablation of cylindrical hollow graphite samples 170-175 mm long with a wall 10-12 mm thick in an air stream in a graphite channel. A room-temperature air stream is passed for 1-20 minutes at a rate of 3.5-300 m/sec over samples heated to 1700-2100°K. The thickness of sample walls is measured before and after the experiments with a precision comparator. Chemical erosion is found to be basic in the ablation mechanism. A formula is given which describes satisfactorily the experimental results for enthalpy factors from 6.5 to 9.3 and Re_x numbers from 10^4 to 6×10^6.

A vast amount of information, basically of a theoretical nature, has been published regarding the problem of the turbulent boundary layer in the presence of a cross stream of matter and nonisothermality. The methods for computing friction and heat exchange are based in most of these works on the semi-empirical turbulence theories of Prandtl and Karman [1-3]. The problem of flow around an ablated surface (combustion, sublimation, evaporation etc.) is reduced to the problem of flow around a semipermeable surface [2-6]. /248[1]

All analytical methods for calculating the turbulent boundary layer under the specified conditions are approximate, are based on several questionable assumptions, and are required in experimental checking. The number of experiments on the combustion of graphite surface in a turbulent boundary layer is quite limited [7].

This article pertains to the experimental determination of the combustion of a graphite surface under the conditions of substantial nonisothermality. The results of the experiment are compared with a method for calculating ablation which is based on the use of limiting relative laws of friction and heat transfer [5].

Experimental Investigation

Our experiments were conducted on a graphite channel. A diagram of our system is illustrated in Figure 1.

[1] Numbers in the margin indicate pagination in the foreign text.

Our apparatus represents a hermetically sealed chamber in which specimen *12* of cylindrical shape, which is being investigated, is placed. The length of the specimen is 170-175 mm and its internal diameter is 36-38 mm. The thickness of its wall is 10-12 mm. The graphite channel is air-blown at room temperature. The air is admitted from the air conductor into tube *4*, and then through diffuser *7* and nozzle *9* into the channel of the specimen under investigation. The exhaust gas is discharged into the atmosphere from channel *16*. The sample, which is made of graphite with a specific gravity of 1670-1690 kg/m^3, is heated by inductor *11* from a high frequency apparatus with a power of 100 kw and an operating frequency of 75 KHz to a temperature of 1700-2100°K.

The temperature of the outer wall of the specimen is measured by optical pyrometer *14* through quartz glass *13*. The measurement error of temperature was ±1.5%.

The temperature drop through the thickness of the wall of the specimen was determined by a special experiment. It did not exceed 3-7% of the measured temperature of the outer surface of the specimen. Furthermore, a temperature correction was introduced for the non-blackness of graphite emission in accordance with the specifications of the pyrometer, which amounted to 30-45°C for the operational temperatures of the specimen. /249

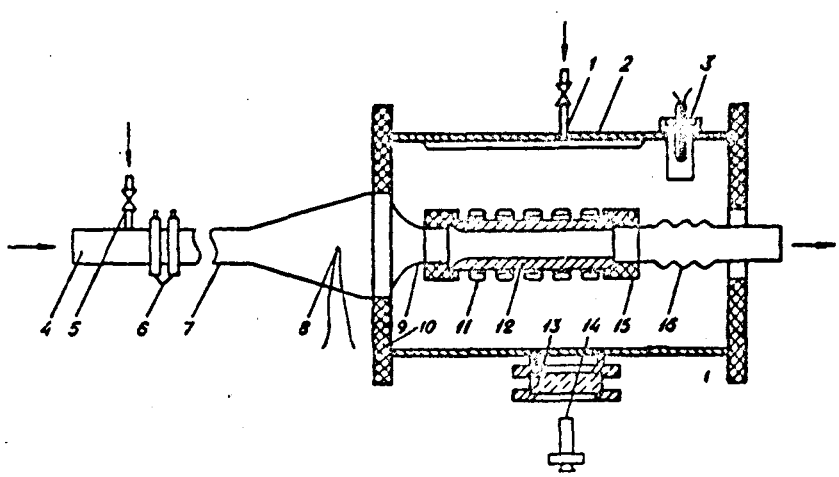

Figure 1. Diagram of Experimental Apparatus

The temperature of the wall of the specimen was measured through the length of the specimen and recorded by the self-recording milliammeter of a VAREG system. Temperature variations on the segment of the sample from 35 to 150 mm did not exceed ±2.5%. A uniform field of velocities at the inlet of the channel was created by profiled nozzle *9*. The flow rate of air was measured according to pressure drops at collar *6* and varied from 3.65 to 258.5 g/sec, whereupon the velocity of the air in the operating channel varied from 3.5 to 300 m/sec. The temperature of the air was controlled by non-chrome-constantan thermocouple *8*. The duration of the experiment varied from 1 to 20 minutes, depending on the flow rate of air. Ablation of the surface of graphite amounted to 1-3 mm (Figure 2).

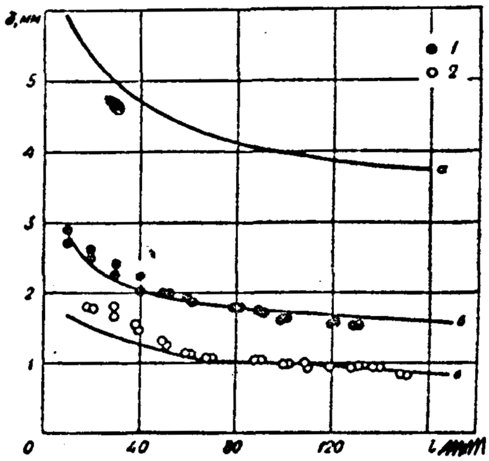

Figure 2. Ablation of Graphite Through Length of Channel. 1 -- Test $\gamma_0\ \omega_0$ = 362 kg/m^2 sec, τ = 63 sec; 3 -- Test $\gamma_0\ \omega_0$ = 67.2 kg/m^2·sec, τ = 144 sec. a -- Ablation as computed by formula (10); b, c -- Ablation as computed by formula (7)

The specimen which we tested was heated to operating temperature over a period of 1-2 minutes. Argon (containing 0.001-0.003% O_2) was blown through tube 5 into the channel in order to avoid ablation of the graphite during the time of the heating of the specimen. /250

The flow of the inert gas through the channel was stopped after the specimen was heated and the required flow rate of air was established during the course of a few seconds. The flow of air was cut off at the conclusion of the test and the inert gas was again blown through the channel until the specimen was completely cooled.

After blowing with the inert gas, the graphite channel was cut into cylindrical sections 10 or 20 mm in length. The ablation of the graphite was measured through four to six diameters on a comparator at the inlet and outlet of each section. Figure 3 illustrates two sections of one of the experiments before and after the test. Uniform erosion through the perimeter of the channel was observed in all tests.

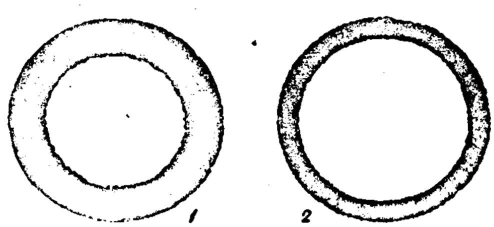

Figure 3. Comparison of Cross Sections of Graphite Sample Before (1) and After (2) Test

The investigation was conducted in seven installments. One of them was carried out with pure argon with a temperature of 2100°K at the surface of the sample. Argon was blown through a channel having an internal diameter of 15 mm at a flow rate of 15 g/sec, whereupon the velocity was 50 m/sec.

No ablation of the graphite was observed after 10 minutes of blowing. We may thus propose that ablation of graphite is attributable to chemical erosion. The magnitude of the parameter of permeability of the wall (oxidation potential) was constant and equal to b_1 = 0.173 for all tests. The parameter of nonisothermality, which was calculated on the basis of the heat content of the gases on the wall and of the primary stream ψ_1, varied from 6.5

to 9.3.

Comparison of Experimental Data with Calculation Method

We selected a graphite sample with a short relative length (4.5-5 caliber). For this reason it is not necessary in generalizing the experimental data to consider the change in the parameters of the gas through the length of the channel in the kernel.

The mode of combustion in the operating temperature range of the wall may be considered as diffusion with the formation primarily of CO [7]. By taking the analog of the processes of heat and mass transmission (Le = Sc = Pr = 1), we arrive at a similarity in the distribution of reduced concentrations and complete enthalpies [8, 6]

$$\frac{h - h_{st}}{h_0 - h_{st}} = \frac{\tilde{K}_i - (\tilde{K}_i)_{st}}{(\tilde{K}_i)_0 - (\tilde{K}_i)_{st}}. \quad (1)$$

From the equation of the mass stream of oxygen near the wall

$$(\tilde{K}_0)_s \rho_{st} w_{st} - \rho D \left(\frac{\partial \tilde{K}_0}{\partial y}\right)_{st} = 0$$

with consideration of equation (1) we find

$$b_1 = \frac{j_{st}}{\gamma_0 w_0 St_h} = \mathrm{Le} \frac{(\tilde{K}_0)_0 - (\tilde{K}_0)_{st}}{(\tilde{K}_0)_{st}} \quad (2)$$ /251

From the equation of the mass stream of the ablated material of the wall

$$\rho_{st} w_{st} = -\rho D \left(\frac{\partial \tilde{K}_c}{\partial y}\right)_{st} + \rho_{st} w_{st} (\tilde{K}_c)_{st}$$

with consideration of (1) we find

$$b_1 = \mathrm{Le}\frac{(\tilde{K}_c)_{st}}{1-(\tilde{K}_c)_{st}}. \qquad (3)$$

By solving jointly equations (2) and (3) for the diffusion mode of combustion we have:

$$b_1 = \frac{3}{4}\,\mathrm{Le}\,(\tilde{K}_0)_0.$$

Thus the "oxidation potential" b_1 is the function of reduced concentration of the oxidizer in the basic stream. For air $b_1 = 0.173$. Consequently, for determining the Stenton criterion

$$\mathrm{St}_h = \frac{J_{st}}{j_0\, w_0\, b_1}$$

It is essential to obtain from the experiment the mass cross stream of the substance on the wall, i.e. the mass velocity of the burned graphite.

For the case where h_{st} = const, $\gamma_0\ \omega_0$ = const, the integral equation of energy has the form:

$$\frac{d\,\mathrm{Re}_h^{**}}{d\bar{x}} = \mathrm{Re}_L\,\mathrm{St}_0\,(\Psi_h + b_h), \qquad (4)$$

where the limiting relative law of heat exchange for $\psi_1 > 1$ for the injection of a homogeneous gas

$$\Psi_h = \frac{4}{b_1(\psi_1 - 1)}\left[\mathrm{arctg}\sqrt{\frac{b_1}{(\psi_1 - 1)(1+b_1)}} - \mathrm{arctg}\sqrt{\frac{b_1\psi_1}{\psi_1 - 1}}\right]^2 \qquad (5)$$

and the law of heat exchange

$$\mathrm{St}_0 = \frac{0{,}0128}{\mathrm{Re}_h^{**0{,}25}\ \mathrm{Pr}^{0{,}75}}, \qquad (6)$$

where

$$\mathrm{Re}_h^{**} = \frac{\rho_0 w_0 \delta_h^{**}}{\mu_{st}}.$$

By solving equation (4) with consideration of (5) and (6), we find: /252

$$\mathrm{St}_h = 0{,}029\ \mathrm{Re}_x^{-0{,}2}\ \mathrm{Pr}^{-0{,}6}\ \Psi_h^{0{,}8}(1+b_1)^{-0{,}2}\left(\frac{\mu_{st}}{\mu_0}\right)^{0{,}2}$$

or

$$K = \frac{\mathrm{St}_h\ \mathrm{Pr}^{0{,}6}(1+b_1)^{0{,}2}}{\Psi_h^{0{,}8}\left(\frac{\mu_{st}}{\mu_0}\right)^{0{,}2}} = 0{,}029\ \mathrm{Re}_x^{-0{,}2} \qquad (7)$$

Since the magnitude of the "high point" of the channel constituted a total of 15-25% during the time of the test, the change in $\gamma_0\ \omega_0$ with time can be considered linear with a sufficient degree of accuracy. Then

$$\bar{j}_{st} = \frac{1}{\tau}\int_0^{\tau} j_{st}\, d\tau, \qquad (8)$$

where j_{st} is the instantaneous mass velocity of the ablation of graphite (see equation (2)).

The integration of equation (8) yields

$$\bar{j}_{st} = \frac{\delta\tau}{\xi} = b_1\, \overline{\gamma_0 w_0}\, \mathrm{St}_h,$$

where

$$\overline{\gamma_0 w_{0}} = \frac{(\gamma_0 w_0)_H \left\{1 + \left[\frac{(\gamma_0 w_0)_k}{(\gamma_0 w_0)_H}\right]^{0.8}\right\}}{2}.$$

Test data, generalized by formula (7) in the form of the dependence of the Stenton criterion on the Reynolds criterion, constructed for the length of the channel, are shown in Figure 4.

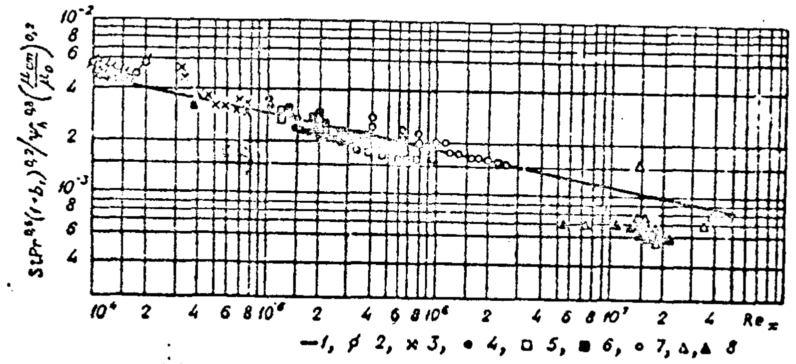

Figure 4. Comparison of Theory with the Experiment
1 -- Calculation by formula (7); 2 -- $\gamma_0\ \omega_0$ = = 3.59 kg/m^2 sec, τ = 1271 sec; 3 -- $\gamma_0\ \omega_0$ = = 10.5 kg/m^2 sec, τ = 509 sec; 4 -- $\gamma_0\ \omega_0$ = 36.6 kg/m^2 sec, τ = 420 sec; 5 -- $\gamma_0\ \omega_0$ = = 198.5 kg/m^2 sec, τ = 73 sec; 6 -- $\gamma_0\ \omega_0$ = = 67.2 kg/m^2 sec, τ = 144 sec; 7 -- $\gamma_0\ \omega_0$ = = 362.0 kg/m^2 sec, τ = 63 sec; 8 -- Tests of Dennison and Bartlett [7]

We see a rather good correspondence of the experiment with the method of calculation (with an accuracy ±13%). It follows from [5] that the effect of the cross stream of the substance on the law of heat exchange is insignificant for the experiments described herein. For the combined effects of nonisothermality and the cross stream of the substance the law of heat exchange may be represented in the form:

$$\left(\frac{St_k}{St_0}\right)_{Re_k^{**}} = \Psi_k = \Psi_t \cdot \Psi_b, \qquad /253$$

where

$$\Psi_1 = \left(\frac{2}{\sqrt{\Psi_1}+1}\right)^2. \qquad (9)$$

$$\Psi_b = \left(1 - \frac{b_h}{b_{кр}}\right)^2.$$

The fraction of the cross stream of the substance is only 12% of the total effect on the Stenton criterion, while nonisothermality reduces the latter by a factor of greater than 3.

Curve 1 in Figure 2 defines linear ablation in accordance with formula

$$St_0 = 0{,}029\, Re_x^{-0,2}\, Pr^{-0,6} \qquad (10)$$

without consideration of the cross stream of the substance and nonisothermality for one of the experiments.

The coefficient of dynamic viscosity for equation (10) was found from the temperature of the basic stream T_0.

As seen in Figure 2, the difference in the evaluation of ablation (of the Stenton criterion) for the specified experiment (ψ_1 = 9.2) with consideration and without consideration of nonisothermality and the cross stream of the substance reaches a factor of 2.5.

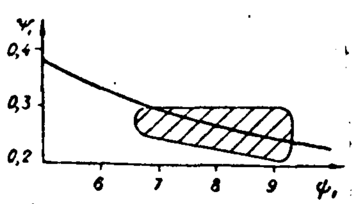

Figure 5. Comparison of Limiting Law of Heat Exchange with the Experiment (shaded area represents the experiments of the authors)

Figure 5 shows the graph for the effect of substantial nonisothermality on the law of heat exchange in a turbulent boundary layer according to the results of our experiments. A comparison shows that the law of heat exchange in the form of (9) is well supported by the test data in the range of variations of the enthalpy factor ψ_1 from 6.5 to 9.3.

Conclusions

1. These tests show that in the range of variations of the enthalpy factor from 6.5 to 9.3 and of the Re_x criterion from 10^4 to $6 \cdot 10^6$

$$\left(\frac{St_h}{St_0}\right)_{Re_h^{**}} = \Psi_1 = \left(\frac{2}{\sqrt{\psi_1}+1}\right)^2,$$

where

$$St_0 = \frac{0{,}0128}{Re_h^{**0.25}\, Pr^{0.75}},$$

and equation

$$Re_h^{**} = \frac{\rho_0 w_0 \delta_h^{**}}{\mu_{st}}.$$

is in satisfactory agreement with the experiment.

2. Chemical erosion, the intensity of which depends on the "oxidation potential" b_1 of the basic stream, is the primary mechanism of the ablation of graphite in the encompassed range of temperatures.

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